UNITED STATES DEPARTMENT OF AGRICULTURE

BUREAU OF ENTOMOLOGY

FOREST INSECT INVESTIGATIONS

SOME TEMPERATURE POINTS AFFECTING THE WESTERN PINE BEETLE

by

J. M. MILLER
Senior Entomologist

Stanford University, California
July 1, 1929

carbon of orig

OUTLINE OF HEADINGS

SOME TEMPERATURE POINTS AFFECTING THE WESTERN PINE BEETLE

by J. M. MILLER
Senior Entomologist
Division of Forest Insects
Bureau of Entomology

Introduction

It is generally recognized that bark beetles, like other living organisms, maintain activity and growth only within a limited range of temperature of the environment in which they live. When these insects are exposed to temperatures a few degrees above or below those under which they carry on their life processes, activity ceases; and death results from exposure to extremes of heat or cold materially beyond the temperatures which result in dormancy.

The fact that wood borers and bark beetles may be killed as a result of the natural heat absorbed by the dead host plant when exposed to sunlight has been known for a number of years. The first published observations of solar heat as a lethal agent to forest insects were made by F.C. Craighead in 1917. He found that the larvae of a cerambycid borer, Cyllene pictus, were killed as a result of absorption of heat when infested logs were exposed to the sun. In 1919 and 1920 experiments carried out by J.E. Patterson and the writer in Oregon and California proved the effectiveness of solar heat in producing killing temperatures in yellow pine bark infested by broods of the western pine beetle. It was found that complete mortality resulted when bark temperatures reached 120 degrees Fahrenheit, and that bark removed from the tree and placed in sunlight reached this and even higher points when the air temperatures in the shade ranged from 85 to 90 degrees.

On the other hand, extreme cold may result in the killing of bark beetle broods, but authentic records of cases where this has occurred under field conditions are scarce. However, at least one outstanding case where high mortality of the western pine beetle took place following a severe cold spell is available. In December, 1924, unusual low minimum temperatures of from 20 to 25 degrees below zero Fahr. were recorded in the vicinity of Bend, Oreg. Following this cold spell, Mr. A.J.Jaenicke of the Forest Service found that a high percentage of the overwintering broods were dead over a considerable area of infested yellow pine. This mortality, which varied from 25 to 80 per cent of the broods, could be accounted for only as a result of freezing of the larvae in the outer bark.

Since 1920 the Forest Insect Station of the Bureau of Entomology at Stanford University, Calif., has been carrying on studies, under both field and laboratory conditions, of the effects of temperatures on the brood stages of the western pine beetle. The object of these studies was to determine (1) the high-temperature points which result in mortality in connection with the use of the solar-heat method of control, and (2) the low temperature points which result in the killing of the overwintering brood stages when severe cold weather occurs in infested areas.

The results of these studies, as far as they have advanced to the present date, are presented in this paper.

BROOD STAGES INCLUDED IN TEMPERATURE STUDIES

The greater part of the material used in these studies consisted of the brood stages found in the outer bark of yellow pine. This was because control by the solar heat method is based on treatment of the infested bark and because freezing is likely to occur only in the overwintering brood stages found in this part of the host tree. This can be understood if we consider briefly the life habits of this species. The parent adults attack the tree by extending winding tunnels through the live cambium, and deposit eggs in notches cut in the sides of these tunnels. After the eggs incubate, the young larvae feed for a time in the cambium and inner bark and then bore directly out into the corky layers of the outer bark, where they complete their development. Each larva cuts in the outer bark its individual feeding gallery and the cell in which it transforms to pupa and new adult. Because of this habit any temperatures affecting the later brood stages must reach the insect through the protective covering of the outer bark. It is while the broods are in these advanced stages that they usually pass through the overwintering period, and control work during either the summer or winter season can be carried on to the best advantage after the larvae have advanced into the outer bark.

Experiments to test the effect of temperatures have therefore been concentrated on brood stages in the outer bark. The temperature of the bark as recorded by imbedded thermometers has been used as an index to mortality of the broods (Fig. 3). Further records have also been made of the effect of air temperatures on larvae and other brood stages after they had been removed from the bark and exposed in open containers.

MORTALITY RESULTING FROM EXPOSURE OF INFESTED BARK TO SOLAR HEAT

In tests of the solar-heat method of control, sections of infested bark were removed from the log and placed on the ground with the inner surface exposed to the sun. Mercurial thermometers were imbedded in the outer bark so that the bulb was buried at the same approximate depth as the pupal cells of the brood. Periodic readings were made of the temperatures recorded by these thermometers, both in sections exposed to the sun and in sections kept in the shade as a check. Corresponding air temperatures in the shade were also recorded, with the object of correlating these with the approximate bark temperatures producing mortality.

The conditions of these tests were varied as to weather conditions and the angle of exposure of bark to the sun's rays. In general it was found that bark removed from the log and placed on the ground at an angle of 60 to 90 degrees to the sun's rays during midday reached temperatures of from 110 to 132 degrees Fahr. when correspondingair temperatures in the shade ranged from 80 to 95 degrees F.

Mortality was determined several days after exposure by cutting up the bark sections so as to expose the broods and counting the number of live and dead individuals.

The results of these studies indicated that:

1. No mortality due to heat results if bark temperatures do not exceed 100 degrees Fahr.

2. A mortality of 40 to 90 per cent results from prolonged exposure of several days when bark temperatures reach maximums ranging from 100 to 115 degrees Fahr.

3. 100 per cent mortality results from an exposure of two or three hours when bark temperatures reach a maximum of 115 to 118 degrees Fahr.

4. 100 per cent mortality results from brief exposures of approximately one hour when bark temperatures reach 120 degrees Fahr. and over.

In these tests the brood stages ranged from half to full grown larvae, with a small percentage of pupae and new adults. No attempt was made to separate the resistance of different brood stages to high temperatures, but in these tests it was apparent that pupae and adults are killed by the same high temperatures that are fatal to the larvae.

Diagrams of comparative air and bark temperatures and resultant mortality are shown in Figs. 1 and 2.

In these tests the factor of relative atmospheric humidity was not isolated from that of temperature. The amount of moisture in the bark is apparently the determining factor in the humidity of the environment of advanced brood stages. Under field conditions the absorption of moisture by the outer bark appears to be very slight, and the moisture content is so nearly constant that this factor can have only a minor influence in modifying the effects of temperatures.

MORTALITY WHEN LARVAE ARE EXPOSED TO WARM AIR TEMPERATURES

As it is impossible to observe the behavior of larvae or other brood stages when exposed in the bark to critical temperatures, a series of laboratory tests was carried out with half to full grown larvae removed from the bark and exposed to varying air temperatures. In one test conditions permitting free evaporation were secured by exposing the larvae to currents of warm air in circulation. As a contrast, conditions in which evaporation was reduced to a minimum were secured by sealing the larvae in glass vials and submerging these under water which was slowly heated through the range of critical temperatures. The results of these tests are shown in Table 1.

TABLE 1

Effect of Warm Air Temperatures on Larvae Removed from Bark

Temp. Fahr.	Lot 1 100 larvae in 5 groups of 20 each in open pasteboard containers; these were exposed at varying heights over an electric plate, permitting free air circulation and evaporation	Lot [illegible] 100 larvae in 5 groups of 20 each in glass vials sealed with paraffin. These vials were submerged in water which was slowly heated through the range of temperatures indicated below
70--90	Normally active	Normally active
90--95	Maximum activity	Maximum activity
95-100	Slight activity; paralysis after prolonged exposures	Activity decreases
100-105	Paralysis after brief exposures; complete mortality after 30 minutes' exposure at 105	Slight activity continues up to 105
105-110	Fatal after brief exposures	Paralysis occurs after prolonged exposure at 108 to 110; ~~larvae paralyzed from brief exposures~~ will recover if returned to normal temperatures
110-115	Fatal after brief exposures	Paralysis occurs after 20 minutes' exposure; larvae do not recover if returned to normal temperatures
115-120	Fatal after brief exposures	Complete mortality occurs after long exposure between 115 and 118; no larvae survive even brief exposures above 118.

Larvae in the sealed containers were killed within the same approximate range of temperatures as those in the outer bark. However, in the open-air containers which permitted free evaporation critical temperatures were 5 to 8 degrees lower and mortality was practically complete at 110 degrees.

The condition termed paralysis was also observed in certain larvae removed from the bark after solar heat tests. When it occurs all movement of the insect ceases and it fails to respond to a stimulus such as the touch of a camel's-hair brush. The larvae do not, however, take on the discolored appearance which develops within a day or so after they are killed. Paralyzed larvae may recover and continue their development if the temperatures producing this condition are not too prolonged. In Lot 2 some of the larvae which were paralyzed at 115 degrees remained in this dormant condition for several months, but eventually turned to the characteristic color of dead larvae and did not recover.

~~XXXXXXXX~~ brood stages in the inner bark

EFFECTS OF LOW TEMPERATURES ON BROOD STAGES IN THE BARK

Determination of the freezing point of insects has been made by Robinson (3) in which the temperature within the body of the insect itself was recorded by the use of the thermocouple. This method gives with considerable accuracy the point at which the free water in the body of the insect freezes, and the still lower undercooling point where crystallization within the cells develops and death results. Robinson also points out that there is a marked difference in the susceptibility of different species to injury by ice formations within the tissues.

In considering the possibility of winter killing of the western pine beetle as a result of unusual low temperatures in the field, reliance upon any accurate data are usually not available aside from weather records in the vicinity of infested areas. It is possible, however, by laboratory methods to determine the freezing temperatures of infested bark which result in mortality to broods in overwintering stages. If temperature stages within the bark of standing infested trees can be correlated with that of the surrounding air, the probability of mortality as a result of abnormal cold spells can readily be determined.

Equipment and Character of Freezing Experiments

During the winters of 1926-27, 1927-28 and 1928-29 a series of tests were carried out by the Bureau of Entomology Laboratory at Stanford University, Calif., to determine the freezing temperatures which are fatal to the western pine beetle. As in the solar heat tests, bark temperatures were recorded by imbedded mercurial thermometers, as no advantage was found in the use of thermocouples for these readings. The method used to determine bark temperatures at the depth of the infesting broods is shown in Fig. 3.

Low temperatures were controlled by the use of a specially designed tank cabinet with a carbon-bisulphide compressing unit. This outfit provided two 10"x16"x24" air compartments in an insulated brine tank, which contained a compressing coil operated by a one-third-horsepower motor. Air temperatures were as low as -24 degrees Fahr. were obtainable in the compartments which were used as containers for infested bark.

Sections of about two square feet of infested bark each were used as units in these freezing tests. Each test, which included a group of six to ten sections, was started with temperatures in the compartments slightly below that of the laboratory and then lowered until the bark temperatures had reached the desired minimum. At determined intervals bark sections were removed from the compartment and placed in the laboratory under normal room temperatures. After 24 hours or more the bark was broken up, the brood removed, and a count made of the live and dead individuals. In doubtful cases the brood was kept under observation for several days or longer until dead individuals could be distinguished by discoloration from dormant ones which were recovering.

The material used was secured from two regional areas representing different climatic conditions. The greater part came from infested trees near Northfork, Calif., where winters are mild and minimum temperatures seldom fall below 10 degrees Fahr. A limited amount of material was also secured from Coeur d'Alene, Id., where winter temperatures occasionally fall as low as -20 degrees Fahr.

Effects on Larvae Under Varying Conditions of Exposure

The method of exposure to low temperatures in the freezing cabinet was varied, first as to the time in which bark was cooled from normal to subzero stages, and second as to the condition of the brood--whether dormant or active. The time during which the bark was allowed to warm back from subzero to normal stages was also varied, but it was soon found that this did not affect the resultant mortality after fatal low temperatures had once been reached.

The results obtained from five differently-treated groups of bark sections from the material collected at Northfork are summarized in Table II. In some of this material a mortality of 1 to 3 per cent of the advanced larvae had already developed in the field at the time the bark was collected, due in part to parasites and to other causes not determined. However, the low mortality from natural causes did not materially affect the results of freezing. Even the higher critical temperatures between 5° and zero Fahr. resulted in mortality considerably in excess of that found under normal conditions.

Results shown in Table II indicate that regardless of the variables due to time of cooling and to dormancy or activity of the broods, mortality of the larvae due to cold appears between 5 degrees above and zero Fahr.; mortality at -5 degrees exceeds 50 per cent, and is practically complete at -10. A diagram of temperatures and corresponding mortality is shown for Lot No. 1 in Fig. 4.

In Lot No. 5 an effort was made to simulate the daily range of temperatures in the field, where cold nights and warm days are a feature of fall weather conditions when the broods are preparing for the overwintering period. The possibility that short periods of cold producing dormancy with intervening periods permitting activity might enable the broods to undergo a hardening process and withstand much lower temperatures was considered in planning this test.

TABLE II

EFFECTS OF LOW TEMPERATURES ON WESTERN PINE BEETLE LARVAE UNDER VARYING CONDITIONS OF EXPOSURE

(Overwintering larvae in yellow pine bark collected at Northfork, Calif.)

	Lot #1	Lot #2	Lot #3	Lot #4	Lot #5
	Bark transferred from field and placed in cabinet after short period in laboratory; temp. lowered from 45° to -16° within 48 hours	Bark transferred from field and placed in cabinet after short period in laboratory; temp. lowered gradually from 45° to -15° within 216 hours	Bark transferred directly from field to cabinet with broods in dormant overwintering condition. Temp. lowered frm. 40° to -15° within 48 hours	Bark transferred from field to laboratory and kept at 60 to 70 deg. for 21 days; then transferred to freezing cabinet with larvae active and developing. Temp. lowered from 60° to -15° in 48 hours	Bark transferred from field to laboratory and subjected to daily changes of temp. ranging from 25° to 70° for 6 days; then transferred to cabinet and lowered from 70° to -15° within 48 hours
	Mortality per cent	Mortality per cent	Mortality per cent	Mortality per cent	Mortality per cent
Check	0	0	3	5	1.5
20°F	0	0	3	4	1.
15"	0	0	2.9	2.5	2.
10	0	0	3	5	0
5"	0	0	2	2.3	17
0"	18	18. (-1°)	31 (-3°)	13	16
-5"	73	79	60.7	57	62 85 (-7°)
-10"	97	100	100	100 (-8°)	100
-15"	100	100	100	100	
-20"					

This assumption was supported in the case of other experiments with broods of the mountain pine beetle, Dendroctonus monticolae Hopk. After the larvae had been subjected to temperatures fluctuating from 20 to 50 degrees Fahr. for a period of several days, they were observed to discharge a considerable amount of excrement from the alimentary canal. After going through this process their resistance to low temperatures increased, and a high percentage of the broods survived temperatures of -15 degrees Fahr.

However, no tendency was observed on the part of larvae of the western pine beetle to empty the alimentary canal, and their resistance to freezing was apparently not increased by any variations of temperature preceding exposure to the fatal freezing points. In fact, Lot 5 showed a perceptible mortality somewhat higher at 5 degrees than in the other material which was carried to subzero temperatures without preliminary fluctuations permitting short periods of activity.

Effect Upon Pupae and New Adults

Some of the material collected from Northfork was kept under laboratory temperatures until the greater part of the broods had developed to the pupa stage, and then lowered through the same range of temperatures as that containing larvae in the preceding tests. A similar test was made of another lot of material after the broods had reached the new-adult stage and were resting in the outer bark. The following table summarizes the results from this material:

TABLE III

MORTALITY OF PUPAE AND NEW ADULTS OF THE WESTERN PINE BEETLE RESULTING FROM LOW BARK TEMPERATURES

Bark Temp. F.	Mortality Per Cent of Pupae	Mortality Per Cent of New Adults
60 to 20 degrees	0	0
15 "	0	12
10 "	0	90
5 "	16	97
0 "	26	100
-5 "	99	100
-8 "	100	100
-10 "	100	100

These results indicate that pupae are somewhat less resistant to cold than the larvae, as mortality was practically complete at -5. Adults, however, appear to be decidedly more susceptible than either larvae or pupae. A high mortality results from exposures at 10 above and mortality is complete at zero.

Effect Upon Eggs in the Cambium

Difficulties not encountered with advanced brood stages in the outer bark were found in obtaining records of temperatures fatal to the egg stage. The eggs are found only in notches excavated by the parent in the cambium, and removal of the bark from the sapwood disturbs the natural conditions for incubation. Mortality due to freezing, therefore, cannot be isolated from other factors unfavorable to development of the eggs after exposure to critical temperatures in their natural environment.

Freshly-attacked logs about 8 inches in diameter in which the parent adults were depositing eggs were selected for these tests. These were cut into blocks about 6 inches in length and subjected in the freezing cabinet to a range of temperatures similar to those used with the other brood stages. Temperature records of the cambium layer were secured by means of a thermometer with the bulb imbedded at this depth under the bark. After exposure the log sections were allowed to stand under laboratory temperatures of 60 to 75 degrees for about ten days. The bark was then shaved off the sapwood so as to uncover the egg galleries, and a count made of eggs which had incubated and those which had failed to develop. A characteristic bluish color distinguished the eggs that had apparently been killed as a result of freezing.

TABLE IV

MORTALITY OF EGGS OF WESTERN PINE BEETLE
RESULTING FROM LOW TEMPERATURES IN THE CAMBIUM

Temperature Fahr. of Cambium	No. Eggs Incubated	No. Eggs Failing to Incubate	Mortality Per Cent.
30	169	9	5
15	54	3	5
10	[illegible]	9	15
5	45	26	36.6
0	51	55	51.9
-5	22	22	50
-10	9	88	90.4
-15	11	76	87.3

It was found that the temperature of the cambium layer within the blocks varied considerably with the moisture content and that they did not cool down uniformly, as was the case with infested bark removed from the log. This factor and the limited amount of material for counts furnish an unsatisfactory basis for determining the mortality per cent; however, the fact that at least ten per cent of the eggs incubated after they had been subjected to temperatures around -10 degrees indicates that this brood stage is more resistant to cold than larvae, pupae or adults.

<u>Effect on Larvae in Outer Bark Saturated with Water</u>

Studies of control by the method of submerging infested logs in water, carried on during the season of 1923, brought out the fact that larvae soon become dormant under water and will remain in this condition for approximately four weeks before mortality occurs. If removed from the water and allowed to dry before this period expires, development of the larvae is resumed. In order to determine whether they lose their resistance to cold in the dormant condition produced by saturation, infested bark was soaked in water for seven days and then subjected to low temperatures. A check consisting of dry bark from the same material was run through a similar range of temperatures. The mortality at critical temperatures resulted as follows:

TABLE V

MORTALITY OF WESTERN PINE BEETLE LARVAE IN SATURATED BARK

Bark Temp. F.	Mortality Per Cent Saturated Bark	Mortality Per Cent Dry Bark
50 deg.	1.7	1.9
24 "	.8	2.9
20 "	9.5	2.
15 "	5.8	2.9
10 "	21.3	2.
5 "	45.4	10.
0 "	72.6	15.
-5 "	95.2	45.
-10 "	100.	100.

This comparison indicates a perceptible lowering of resistance to freezing as a result of saturation of the bark. However, the degree of saturation necessary to produce dormancy rarely if ever occurs in standing infested trees where the outer bark remains dry under ordianry exposure to weather. Saturation of the outer bark does occur, however, in submerged logs.

EFFECT OF LOW AIR TEMPERATURES ON LARVAE REMOVED FROM OUTER BARK

In addition to tests with brood stages in the outer bark, a large number of larvae were exposed to varying temperatures in open pasteboard containers where their behavior could be observed. It was found that activity slowed down at about 50 degrees, and apparent dormancy set in between 45 and 40 degrees. Very little change could be observed below 40 degrees until temperatures between 15 and 10 degrees were reached. At this point the body of the larva becomes rigid and takes on a peculiar white color. This represents the freezing point, where the free water in the body of the insect crystallizes. If larvae are brought back from this point to temperatures of 45 degrees or more, normal appearance and activity are resumed. However, if the temperature, instead of being raised, is lowered from the freezing point to subzero stages, mortality results and there is no recovery of activity if the insects are later brought back to temperatures above 45 degrees. The following were the critical temperatures established by these tests:

TABLE VI

MORTALITY OF WESTERN PINE BEETLE LARVAE
EXPOSED TO AIR TEMPERATURES

Air Temperature F.	Mortality Per Cent of Larvae
65 [illegible] 10 degrees	0
5 "	18
0 "	18
-5 "	56
-8 "	100

Material was sent to Mr. William Robinson at Chicago, who determined the freezing and undercooling points of individual larvae by the special apparatus which he has devised. His records of 15 individual larvae show that the freezing point occurred from 12 to 14 degrees above zero, while the undercooling point where mortality resulted occurred from -2 to 8 degrees. The general effect of both high and low temperatures and the results of tests of brood stages in the bark are shown in Table VII.

EFFECT OF LOW TEMPERATURES ON PARASITES AND PREDATORS IN THE BARK

Predators and parasites of the western pine beetle were found in many of the infested bark sections used in the above tests, and observations secured as to their mortality at various points. However, this material was not sufficient in quantity to furnish a satisfactory basis for the determination of critical temperatures, although the data secured indicate that these forms differ in their freezing points from the western pine beetle, and that the temperatures reached in these tests were not low enough to kill the larvae of a chalcid parasite.

Temnochila virescens (larvae); mortality occurred between 10 degrees and zero

Thanasimus nigriventris (larvae) idem

Aulonium longum (adults); mortality occurred at about 10 deg.

Chalcid larvae (probably _Cecidostiba burkei_); no mortality occurred, although several individuals were exposed to -20 deg. F.

EFFECTS OF LOW TEMPERATURES IN REGIONS
WHERE WINTER MINIMUMS FALL BELOW ZERO FAHR.

It is evident that in the northern limits of the distribution of the western pine beetle winter temperatures fall below the critical points indicated by the above tests. Although weather records show that minimum temperatures as low as -20 Fahr. may occur at times, at least part of the overwintering beetle population survives these cold spells. This may be due to a resistance which has been built up within the region by natural selection, or it may be due to the fact that temperatures in the bark on infested trees do not reach the low points recorded by weather thermometers in the surrounding air.

Through the cooperation of Mr. J.C. Evenden of the Bureau of Entomology Field Station at Coeur d'Alene, Id., where the winter climate is colder than in the yellow pine belt of the Sierra Nevada region, about 25 square feet of infested bark was mailed to the laboratory at Stanford University and subjected to low temperatures in the freezing cabinet. This bark contained broods of advanced larvae which had been in an overwintering condition for several months. During this period minimum temperatures as low as -10 Fahr. had been recorded in the vicinity where the material was collected. Bark sections from this material were lowered from 55 to -18 degrees with the following results:

TABLE VII

MORTALITY OF WESTERN PINE BEETLE LARVAE WHICH HAD OVERWINTERED IN YELLOW PINE BARK AT COEUR D'ALENE, ID.

Bark Temp. F.	Mortality Per Cent
55 to 10 deg.	0
5 "	16
0 "	0
-5 "	49
-10 "	75
-12	89
-18	100

Although partial mortality appeared within the same range of critical temperatures as in the material from Northfork, the striking difference is in the degree of survival after -5 degrees had been reached. This amounted to 24 per cent survival at -10 and 11 per cent survival at -12 degrees. Apparently these broods had developed a partial resistance to temperatures which were 100 per cent fatal to broods which had overwintered under warmer climatic conditions. However, this resistance was not sufficient to withstand more than 10 degrees below the temperatures which were fatal to the material collected at Northfork.

DISPERSION BETWEEN AIR AND BARK TEMPERATURES IN THE FIELD

The fact that broods of the western pine beetle do survive where weather records show minimum air temperatures below those which were found to be fatal in the bark, indicates that the infested bark on standing trees does not become as cold as the surrounding atmosphere and therefore does not cool down to the critical points. This seems apparent, as the infested bark is in contact with the moist sapwood of the tree, which in turn connects with the root system in the soil. This position gives contact to a reserve of accumulated warmth which prevents rapid cooling of the bark. It would appear that only prolonged periods of subzero temperatures can chill the bark sufficiently to produce temperatures fatal to the broods.

Two series of records secured by Messrs. J.C. Evenden and H.J. Rust support this assumption. In January 1927 and again in January 1928 periods of subzero weather occurred at Coeur d'Alene, Id. During these cold spells, weather thermometers were placed in the bark on the north and south sides of an infested standing tree. At the same time thermometers were suspended in the air on the north, east, south and west sides of the tree. Readings were taken hourly during a period of 25 hours. The lowest point recorded in the readings of air temperature was -6 F. when the corresponding bark temperatures were 4 and 6 above zero F. This shows a dispersion of 10 and 12 degrees between the air and bark temperatures. As the air temperatures rose this dispersion decreased, and both air and bark temperatures corresponded closely at 12 degrees above zero. No appreciable mortality occurred in the broods, which would be expected, since critical temperatures were not reached in the bark.

Further records of the comparative air and bark temperatures and a study of the effects of extreme low temperatures in the field are necessary before it will be possible to determine the expectancy of mortality to broods of the western pine beetle as a result of winter freezing.

TABLE VIII

RANGE OF TEMPERATURES AFFECTING BROOD STAGES OF THE WESTERN PINE BEETLE

Temp.F.	
120	Fatal to all brood stages after brief exposures
118–115	Complete mortality after long exposures; paralysis of larvae from which they do not recover occurs after 20 minutes' exposure
115–110	Paralysis of larvae occurs but recovery possible if exposure not prolonged
110–105	Paralysis of larvae occurs after prolonged exposures; will recover if returned to normal temperatures
105–100	Larvae become sluggish, showing slight activity
100–95	Activity of larvae decreases
95–55	Maximum activity of larvae
55–45	Activity of larvae decreases
45–40	Larvae become sluggish and apparent dormancy sets in
40, 35, 20, 15	Dormancy occurs in all brood stages
15–10	Larvae freeze but recover if warmed back to active temperatures
10–5	Critical temperatures for adults; high mortality occurs at 10°; low mortality of larvae and pupae may occur at 5°
5, 0, -5, -8	Critical temps. for larvae and pupae; mortality at 5 exceeds 80%
-10, -15	Fatal to all brood stages; a low percentage of the eggs and of larvae which are adapted to severe winter climates may survive these temperatures
-20	Fatal to all brood stages

SUMMARY

1. Fatal temperatures are of importance in both the artificial and natural control of the western pine beetle (<u>Dendroctonus brevicomis</u> Lec.) Temperatures in the bark that are high enough to result in mortality are essential in the use of the solar heat method of control. Low temperatures in the field which result in death of the broods from freezing may materially reduce the beetle population in infested areas.
2. Temperatures affecting brood stages of the western pine beetle while in the overwintering condition must reach the insects through the protective covering of the outer bark. The same consideration applies to the brood stages treated by the solar heat method of control. Critical environmental temperatures must therefore occur in the outer bark.
3. When infested bark is removed from the log and placed where it is exposed to sunlight during the midday period, it will reach temperatures ranging from 110 to 130 degrees when the corresponding air temperature ranges from 80 to 95 degrees Fahr. A partial mortality of the broods will result if bark temperatures range from 100 to 115 degrees daily for a period of several days. Complete mortality is assured if bark temperatures reach 115 to 118 degrees for a period of two hours or more. No broods survive a brief exposure if the bark reaches a maximum of 120 degrees.
4. When larvae are removed from the outer bark and exposed to warm air under conditions which retard evaporation, mortality occurs at about the same points of temperature as in the bark. If rapid evaporation is permitted, paralysis and mortality occur at points about five degrees lower than in the bark.

5. Mortality of the larvae following freezing results when bark temperatures are lowered below zero Fahr. Partial mortality occurs at zero in broods which overwinter in the yellow pine belt of the Sierra Nevada region; mortality at -5 degrees exceeds 60 per cent, and no larvae survive at -10 degrees Fahr. Temperatures within the range from zero to -10 are consistently critical, regardless of the rate at which the temperature of the bark is lowered or warmed back from subzero to normal temperatures; complete mortality develops within this range regardless of whether the larvae are actively developing or dormant at the time the bark temperature is lowered to the critical points.

6. High mortality of the pupae occurs between 5 and -5 and is complete at -8 degrees Fahr.

7. High mortality of the adults occurs between 12 and 5 degrees Fahr. and is complete at zero.

8. Partial mortality of eggs in the cambium occurs between 5 and -10 degrees Fahr. The mortality recorded at -15 degrees was around 90 per cent, indicating greater resistance to cold than the other brood stages.

9. When larvae become dormant through excessive saturation of the bark with water they are less resistant to cold, and about 20 per cent mortality occurs at 10 degrees. Complete mortality, however, does not occur until points between -5 and -10 degrees Fahr. are reached.

10. When larvae are removed from the bark and exposed to cold air, complete mortality occurs between 5 and -8 degrees Fahr.

The point at which the larvae freeze but recover if warmed back to active temperatures occurs between 10 and 15 degrees Fahr.

Larvae become dormant at about 45 degrees and show no further change until the freezing point is reached.

Maximum activity and development of the larvae occur between 55 and 90 degrees Fahr.

11. Broods which overwinter in regions where the minimum winter temperatures are below zero apparently develop greater resistance to cold than in regions with mild winter climates. Larvae which had passed through the overwintering condition at Coeur d'Alene, Id., where air temperatures of -10 degrees had been recorded, developed high mortality when bark temperatures were reduced through the range from zero to -10 degrees Fahr. However, about 25 per cent survived -10, but mortality was practically complete at -18 degrees Fahr. The extent of resistance to cold developed by regional conditions apparently does not exceed 10 degrees Fahr. of temperature.

12. The outer bark on standing infested trees cools down much more slowly than the surrounding air, and does not reach the minimum temperatures recorded by weather thermometers. Records secured at Coeur d'Alene, Id., during two periods of subzero weather indicate that the minimum bark temperatures are 10 to 12 degrees higher than minimum air temperatures. Further records are needed to correlate this dispersion between bark and air temperatures to determine the probability of winter killing in infested areas.

10. When larvae are removed from the bark and exposed to cold air, complete mortality occurs between 5 and -8 degrees Fahr.

The point at which the larvae freeze but recover if warmed back to active temperatures occurs between 10 and 15 degrees Fahr.

Larvae become dormant at about 45 degrees and show no further change until the freezing point is reached.

Maximum activity and development of the larvae occur between 55 and 90 degrees Fahr.

11. Broods which overwinter in regions where the minimum winter temperatures are below zero apparently develop greater resistance to cold than in regions with mild winter climates. Larvae which had passed through the overwintering condition at Coeur d'Alene, Id., where air temperatures of -10 degrees had been recorded, developed high mortality when bark temperatures were reduced through the range from zero to -10 degrees Fahr. However, about 25 per cent survived -10, but mortality was practically complete at -18 degrees Fahr. The extent of resistance to cold developed by regional conditions apparently does not exceed 10 degrees Fahr. of temperature.

12. The outer bark on standing infested trees cools down much more slowly than the surrounding air, and does not reach the minimum temperatures recorded by weather thermometers. Records secured at Coeur d'Alene, Id., during two periods of subzero weather indicate that the minimum bark temperatures are 10 to 12 degrees higher than minimum air temperatures. Further records are needed to correlate this dispersion between bark and air temperatures to determine the probability of winter killing in infested areas.

LITERATURE CITED

(1) PAYNE, NELLIE M.

1926. FREEZING AND SURVIVAL OF INSECTS AT LOW TEMPERATURES. Quar.Rev.Biol.,Vol.1,No.2,pp.270-282,April.

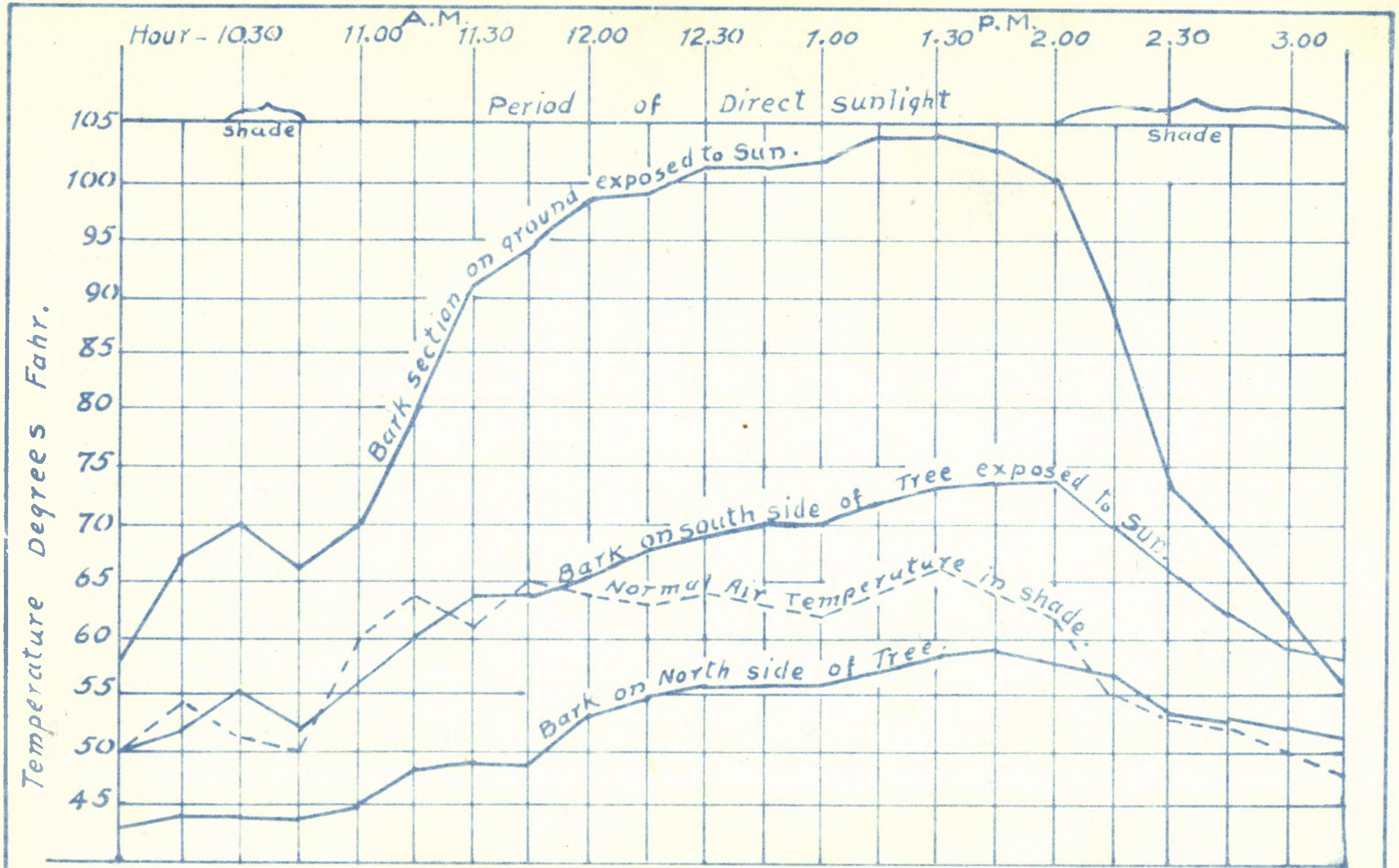
(2) 1927. TWO FACTORS OF HEAT ENERGY INVOLVED IN INSECT COLD HARDINESS. Ecology,Vol.8,No.2,pp.194-196.

(3) ROBINSON, WILLIAM

1928. DETERMINATION OF THE NATURAL UNDERCOOLING AND FREEZING POINTS IN INSECTS. Jour.Agr.Res.,Vol.37,No.12, Dec.15,pp.749-755.

(4) CRAIGHEAD, F.C.

1920. DIRECT SUNLIGHT AS A FACTOR IN FOREST INSECT CONTROL. Proc.Ent.Soc.Washington,Vol.22,No.5.



Test B. Chart of Comparative Temperatures of infested bark under Different exposures. Feb. 11, 1920.

Fig. 1

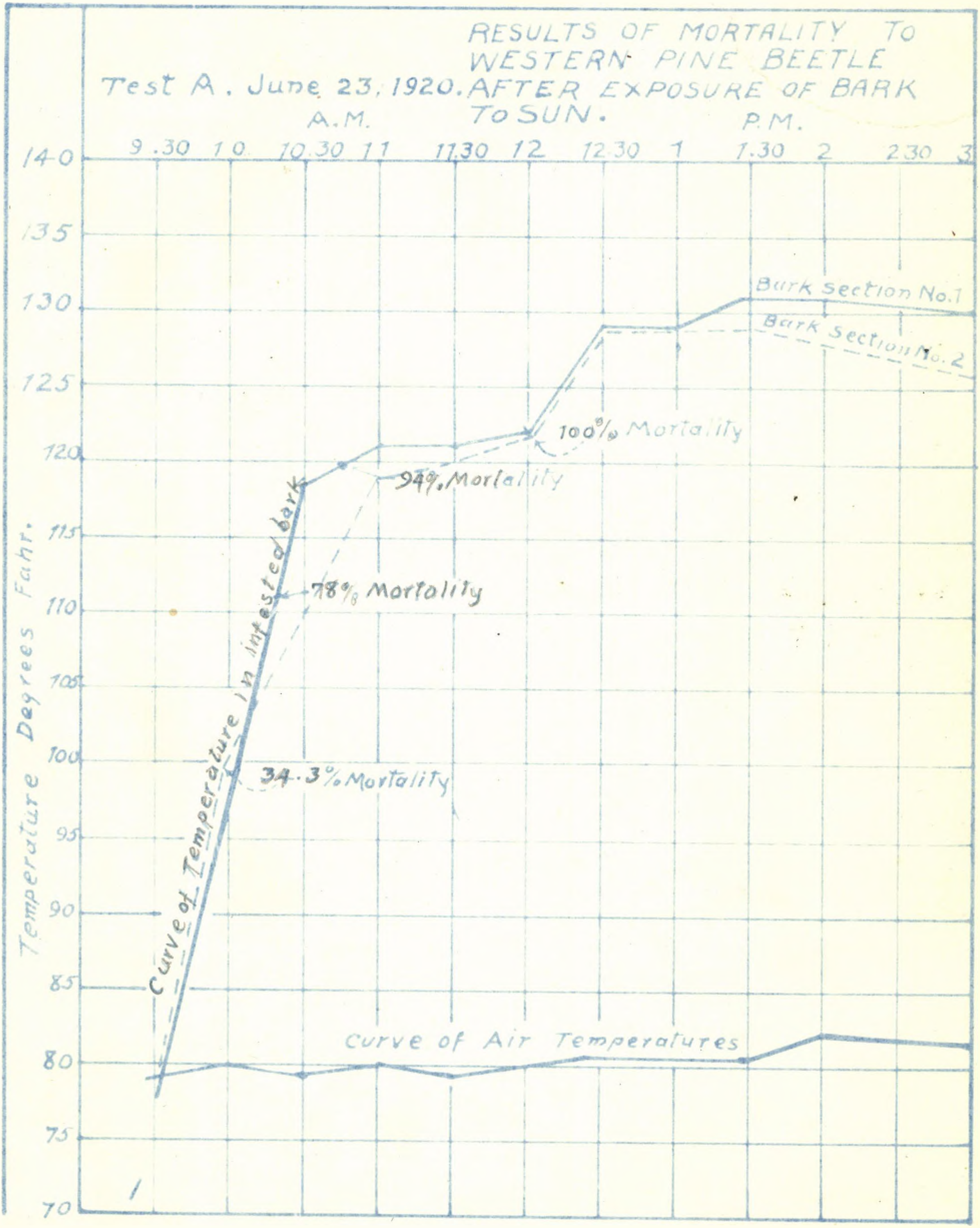

RESULTS OF MORTALITY TO WESTERN PINE BEETLE AFTER EXPOSURE OF BARK TO SUN.
Test A. June 23, 1920.
A.M.
P.M.
9.30
10
10.30
11
11.30
12
12.30
1
1.30
2
2.30
3
140
135
130
125
120
115
110
105
100
95
90
85
80
75
70
Temperature Degrees Fahr.
Bark Section No. 1
Bark Section No. 2
100% Mortality
94% Mortality
78% Mortality
34.3% Mortality
Curve of Temperature in infested bark
Curve of Air Temperatures

Fig. 2

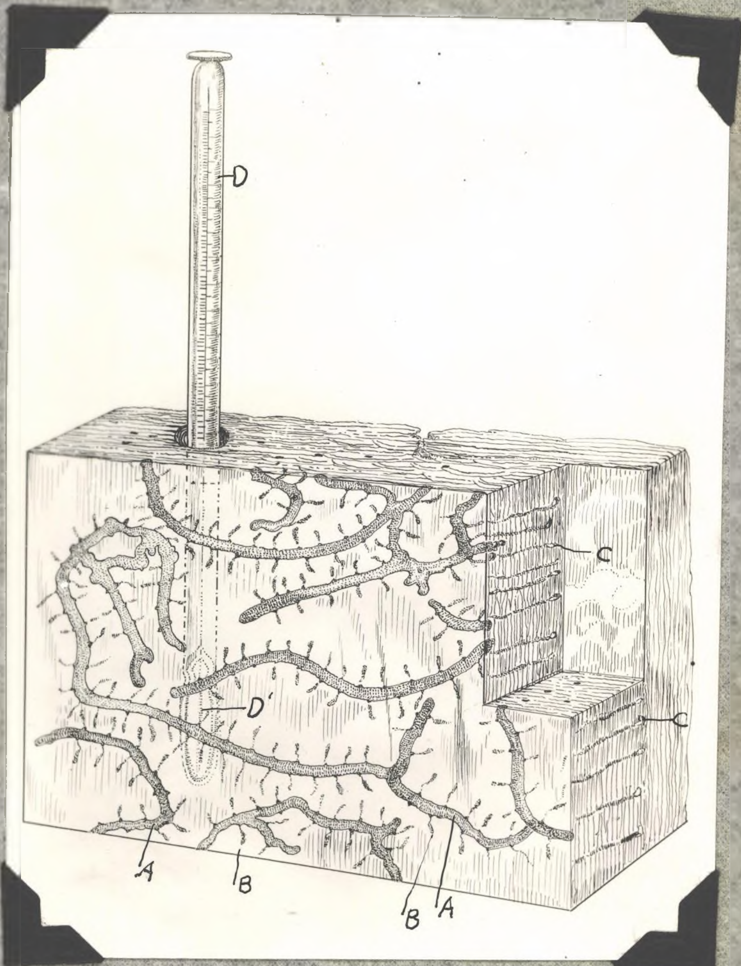


FIG. 3. SECTION OF YELLOW PINE BARK SHOWING POSITION OF THERMOMETER USED IN RECORDING TEMPERATURES

a. Egg galleries of Western Pine Beetle on inner surface of bark

b. Mines of young larvae in inner bark

c. Mines of advanced larvae and pupal cells in outer bark

d. Mercurial thermometer with scale extending above bark

d_1. Bulb of thermometer imbedded at depth of pupal cells

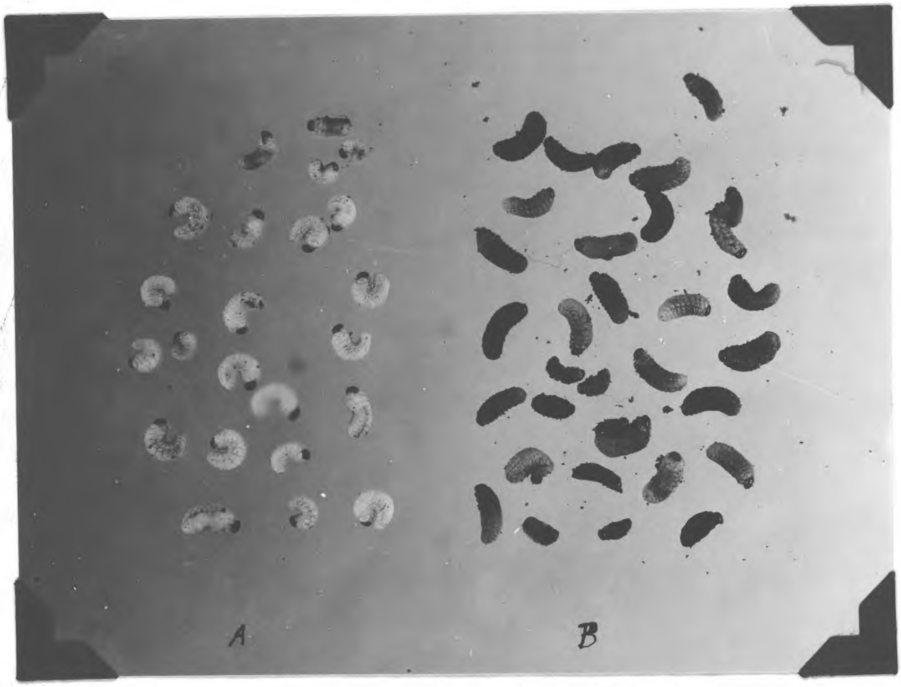


FIGURE 4. LARVAE OF WESTERN PINE BEETLE REMOVED FROM BARK TWO DAYS AFTER EXPOSURE TO A TEMPERATURE OF -5 DEGREES FAHR.

A. 23 living larvae which survived this temperature; these are normal color and active when disturbed. When not in motion they usually lie in a curled position with head and anal ends turned to9ard ventral surface of body.

B. 32 dead larvae; these are discolored and snow no activity. The body tissues are soft and the larvae usually lie in a distended position.

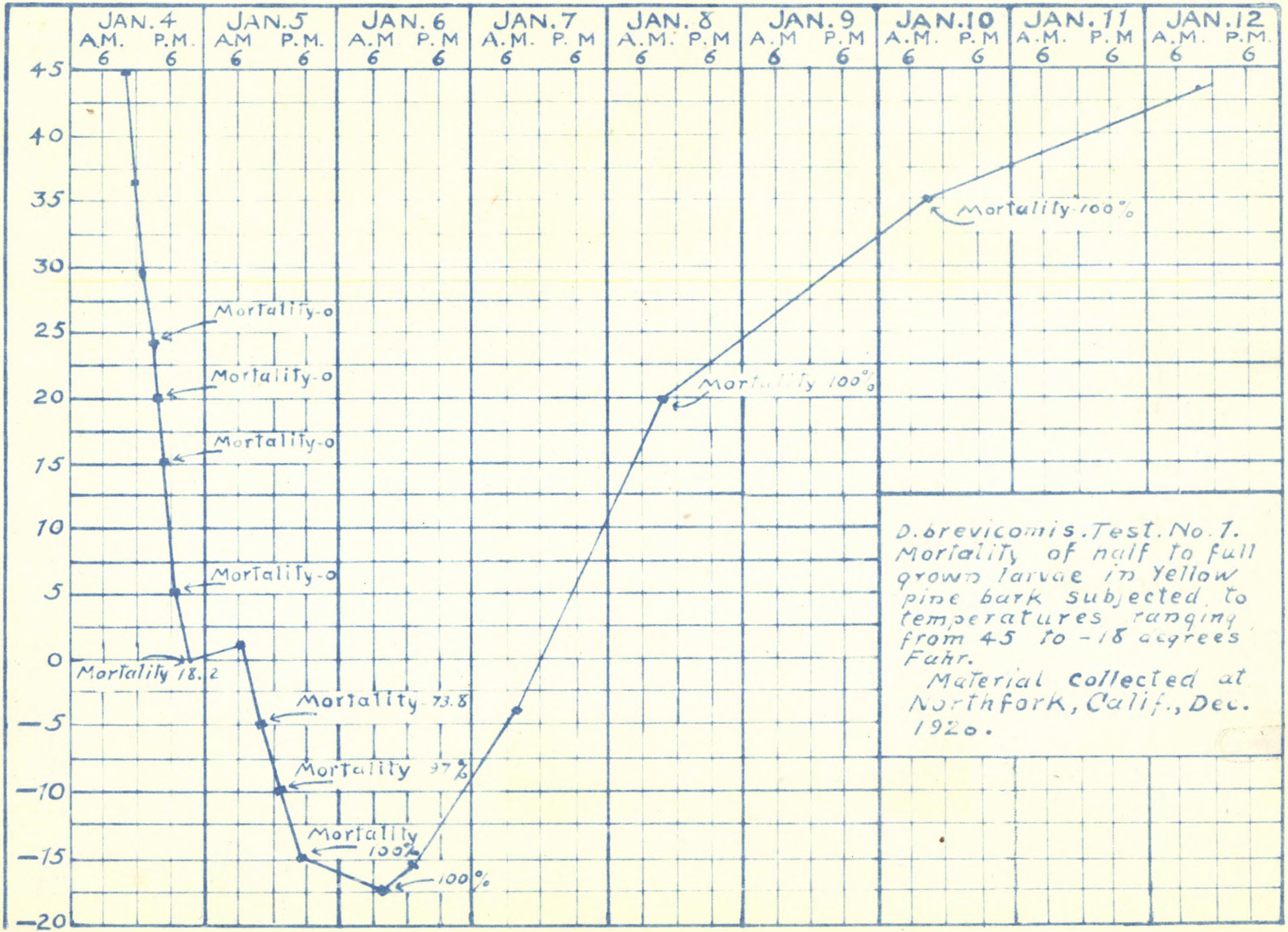

JAN. 4 A.M. 6 P.M. 6
JAN. 5 AM 6 P.M. 6
JAN. 6 A.M 6 P.M 6
JAN. 7 A.M. 6 P.M 6
JAN. 8 A.M. 6 P.M 6
JAN. 9 A.M 6 P.M 6
JAN. 10 A.M. 6 P.M. 6
JAN. 11 A.M. 6 P.M 6
JAN. 12 A.M. 6 P.M. 6
45
40
35
30
25
20
15
10
5
0
−5
−10
−15
−20
Mortality-0
Mortality-0
Mortality-0
Mortality-0
Mortality 18.2
Mortality 73.8
Mortality 97%
Mortality 100%
100%
Mortality 100%
Mortality 100%
D. brevicomis. Test. No. 1. Mortality of half to full grown larvae in Yellow pine bark subjected to temperatures ranging from 45 to -18 degrees Fahr.
Material collected at Northfork, Calif., Dec. 1920.

Fig. 5